Numerical Weather Prediction

Assimilating MODIS polar winds in the Met Office system

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Document History

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ABSTRACT

The MODIS winds, developed at the Cooperative Institute for Meteorological Satellite Studies (CIMSS), have shown potential as a useful new dataset for NWP models. The winds provide information in the data-sparse polar regions and complement the conventional low and mid-latitude geostationary atmospheric motion vectors (AMVs).

The MODIS assimilation experiments at the Met Office and elsewhere show encouraging results, with most improvement in the height, temperature and wind fields in the mid to high latitudes at medium range. MODIS winds have been assimilated operationally in the Met Office global model since 8th February, 2005.

Future changes to the MODIS product should lead to improvements in the timeliness, quality and coverage of the winds, which should allow NWP centres to use more data and gain greater impact operationally.

1. INTRODUCTION

Until the development and real-time distribution of the MODIS wind dataset by the Cooperative Institute for Meteorological Satellite Studies (CIMSS) in 2002, the only wind observations available for global NWP in the polar regions (polewards of 65° latitude) were a few radiosonde and aircraft reports. The MODIS winds provide important new information in the data-sparse polar regions and have the potential to greatly improve polar wind analyses, which should in turn improve global forecasts. MODIS wind assimilation experiments at several centres including the European Centre for Medium Range Weather Forecasting (ECMWF) and the Global Modeling and Assimilation Office (GMAO), NASA, have indeed shown improvements in polar analyses and forecast skill (Bormann & Thépaut, 2003; Key et al., 2003). Many NWP centres now use these winds operationally including the Met Office, ECMWF, GMAO, CMC and JMA.

The MODIS winds, like the well-established geostationary AMVs, are produced by tracking clouds or areas of water vapour through consecutive satellite images. The MODIS winds are derived using the IR window channel and WV absorption channel. MODIS (Moderate Resolution Imaging Spectroradiometer) is an instrument on board the polar-orbiting Terra and Aqua satellites. Although the geostationary and polar winds are produced using the same method, there are several important differences. There is a much longer time lag between the valid time of the observations and their arrival time at NWP centres, restricting their usage in forecast models. Another major difference is the longer time interval between consecutive images. For the MODIS polar winds the interval is approximately 100 minutes, longer than the 10-30 minute intervals used for geostationary AMVs and much longer than the optimal 5-10 minutes for cloudy tracers determined by experiments at EUMETSAT and CIMSS (e.g. Velden, 2000). With the MODIS winds there are also complications due to the different viewing geometries of successive orbits and difficulties with height assignment due to the low atmospheric water vapour amounts and thin clouds that are typical of the Arctic and Antarctic (Key et al., 2003). In view of these difficulties, it is perhaps unsurprising that not all assimilation experiments using the MODIS polar winds have produced positive results.

In this paper, the results of monitoring investigations and MODIS assimilation experiments are discussed. Some questions addressed include how the winds from Terra and Aqua compare and whether the newer NESDIS MODIS wind dataset are better than the original CIMSS dataset. The results of the latest assimilation experiments are presented and plans for the future are highlighted.

2. POLAR CLIMATOLOGY

What benefit can we expect to get from assimilating polar winds? We have already ascertained that there is little polar wind information assimilated operationally and certainly nothing that provides good spatial coverage. Therefore the MODIS winds could be important to capture the location, shape and strength of features in the wind field in the polar regions.

Some of the most important features for the evolution and development of weather systems are the jet streams. There are two important jet-streams in each hemisphere. The first, the subtropical jet is a relatively constant westerly flow around 30° south and north of the equator (see Figure 1). The second, the polar front jet is more variable, tends to be more meridional and occurs closer to the poles where the polar air meets the warmer air in the mid-latitudes.

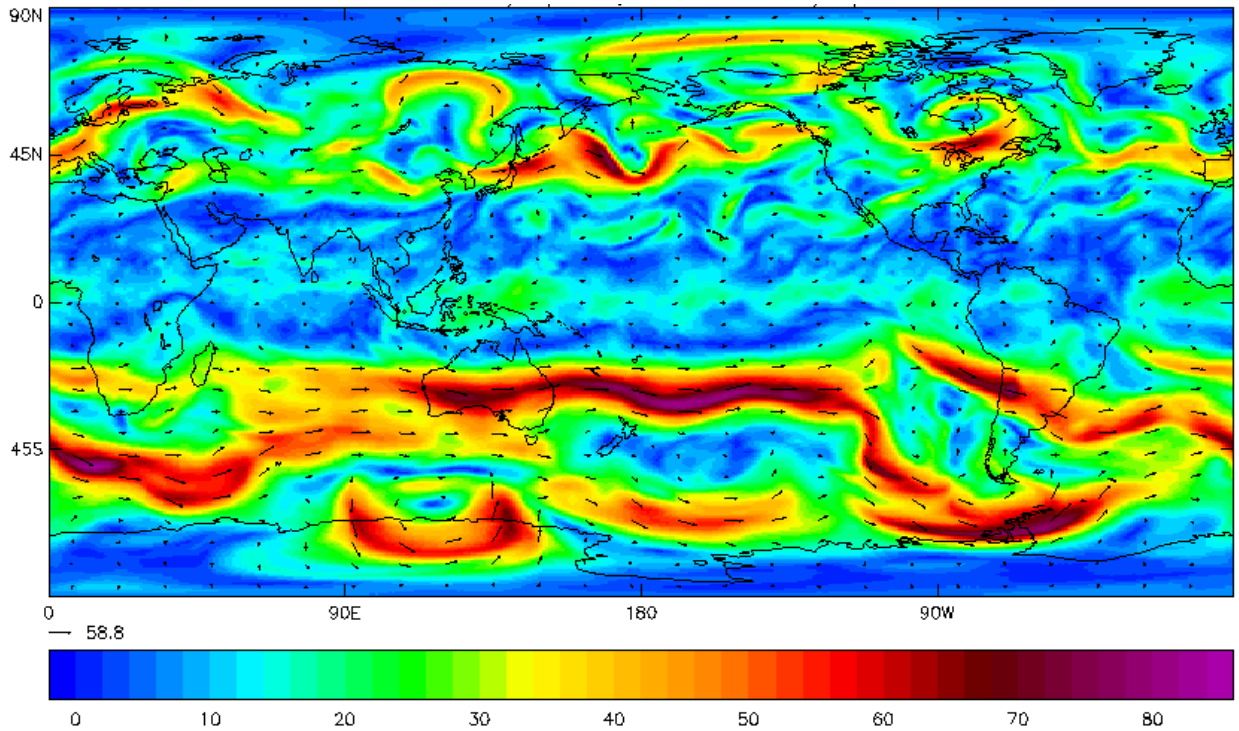


Figure 1: *Example Met Office global trial 250 hPa wind field at 12:00 on 20th August, 2004. Speeds are in m/s. Note the strong westerly subtropical jets at about 30S and 45N. Also notice the more meridional westerly polar front jets at higher latitudes. Some sections of the polar front jets extend into the regions covered by the MODIS polar winds.*

Figure 2 shows how the MODIS polar winds are able to delimit the polar front jet where it is deflected towards the poles. Figures 1 and 2 show winds for approximately the same time and level. Although the projection and scales are different it is possible to identify many of the same features in both plots. One cautionary note is that the MODIS polar winds are most abundant at mid-levels below the fastest jet winds at 250-300 hPa.

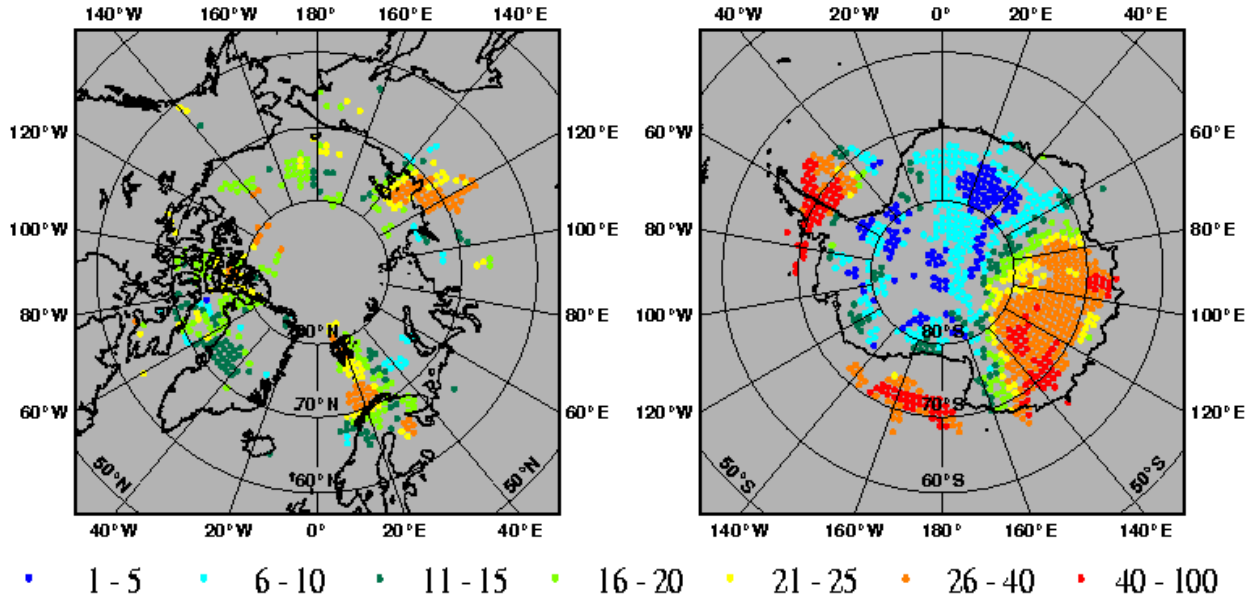


Figure 2: *Mean observation speed of the NESDIS MODIS IR upper level (1-400 hPa) winds for 20th-21st August, 2004. Speeds are in m/s.*

The MODIS polar winds will also be able to provide information on more minor features in the wind field and should help to constrain the location of high and low pressure systems. Some low pressure systems that develop in the polar regions subsequently move into the mid-latitudes and can bring severe weather to these areas. Polar lows are a particular sub-set of low pressure systems that are often associated with very heavy snowfalls and strong winds. They mostly develop over the cold polar seas and normally have a short life-

span. They can be identified in satellite imagery, typically having a comma-shape. They are, however, normally small, only 200-1000 km in size. These systems can only be resolved in models with good resolution (~50 km) and it is debateable whether the MODIS winds thinned in 200 km boxes, as used at the Met Office, would provide enough information to constrain them.

3. TIME DELAY

Before discussing the assimilation strategy for the MODIS winds, it is worth considering the timing and distribution of the winds in a bit more detail.

The MODIS winds are not available as quickly as the geostationary winds. This is partly due to delays getting the imagery data from the satellite to the ground station and partly due to the longer time interval between images. The typical delay between observation time and receipt time is 3.5 to 7 hours. Figure 3 shows the time delay in minutes as a function of observation time for one day in January, 2005.

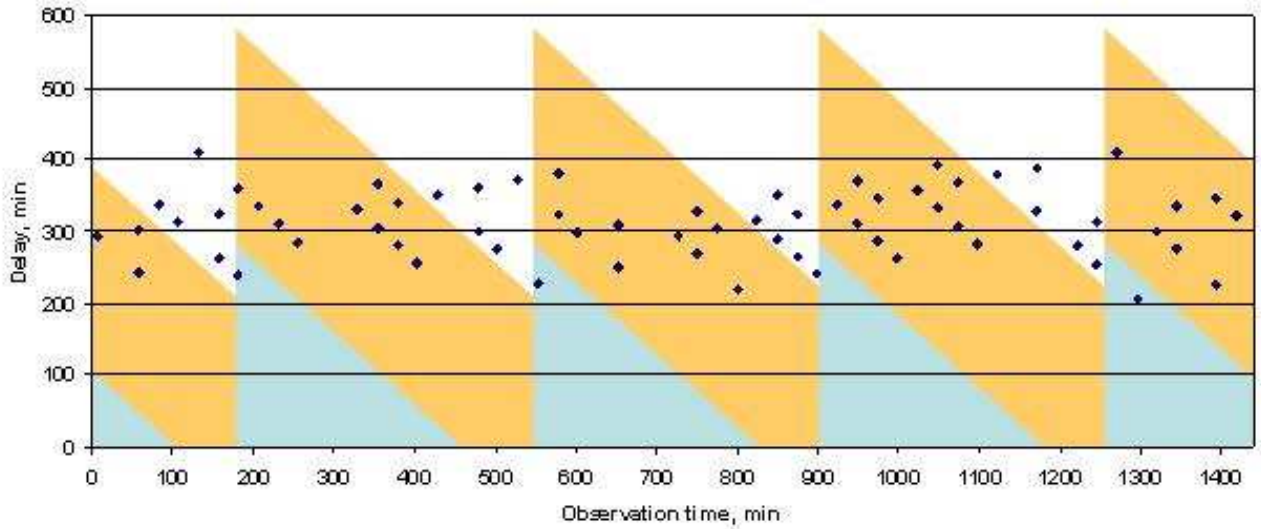


Figure 3: *Time delay of the NESDIS MODIS winds as a function of observation time for data valid on 16th January, 2005. Each blue dot represents one batch of data. The blue triangles show the times accepted by the main forecast runs with time cut-offs of 1 hour 45 minutes. The orange triangles show the times accepted by the update runs with time cut-offs of 6 hours 45 minutes.*

The polar winds differ from the geostationary winds in another important way. For the geostationary winds, the full earth disc is scanned every 10-30 minutes and a full set of AMVs produced every 1-6 hours. The polar winds are different as the MODIS instrument only slowly builds up information in the polar regions (see Figure 4). Therefore, although Figure 3 shows data with observation times at approximately 25 minute intervals, it actually takes 2 satellites about 6 hours to build up full polar coverage (see Figure 5).

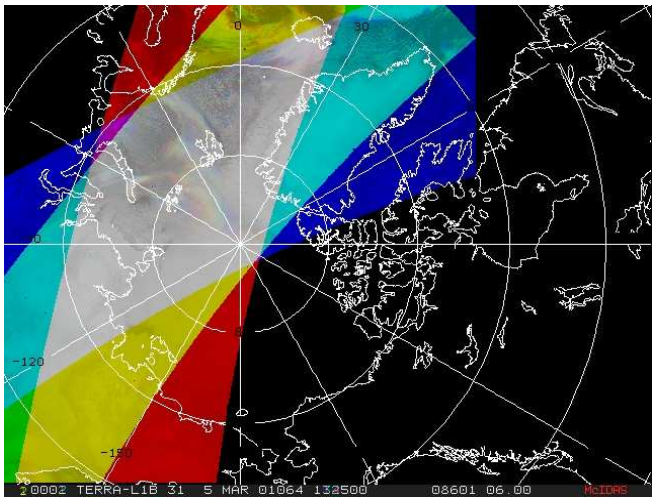


Figure 4: *MODIS winds can be calculated in the overlapping region between 3 successive overpasses (area shown in white). Picture courtesy of CIMSS*

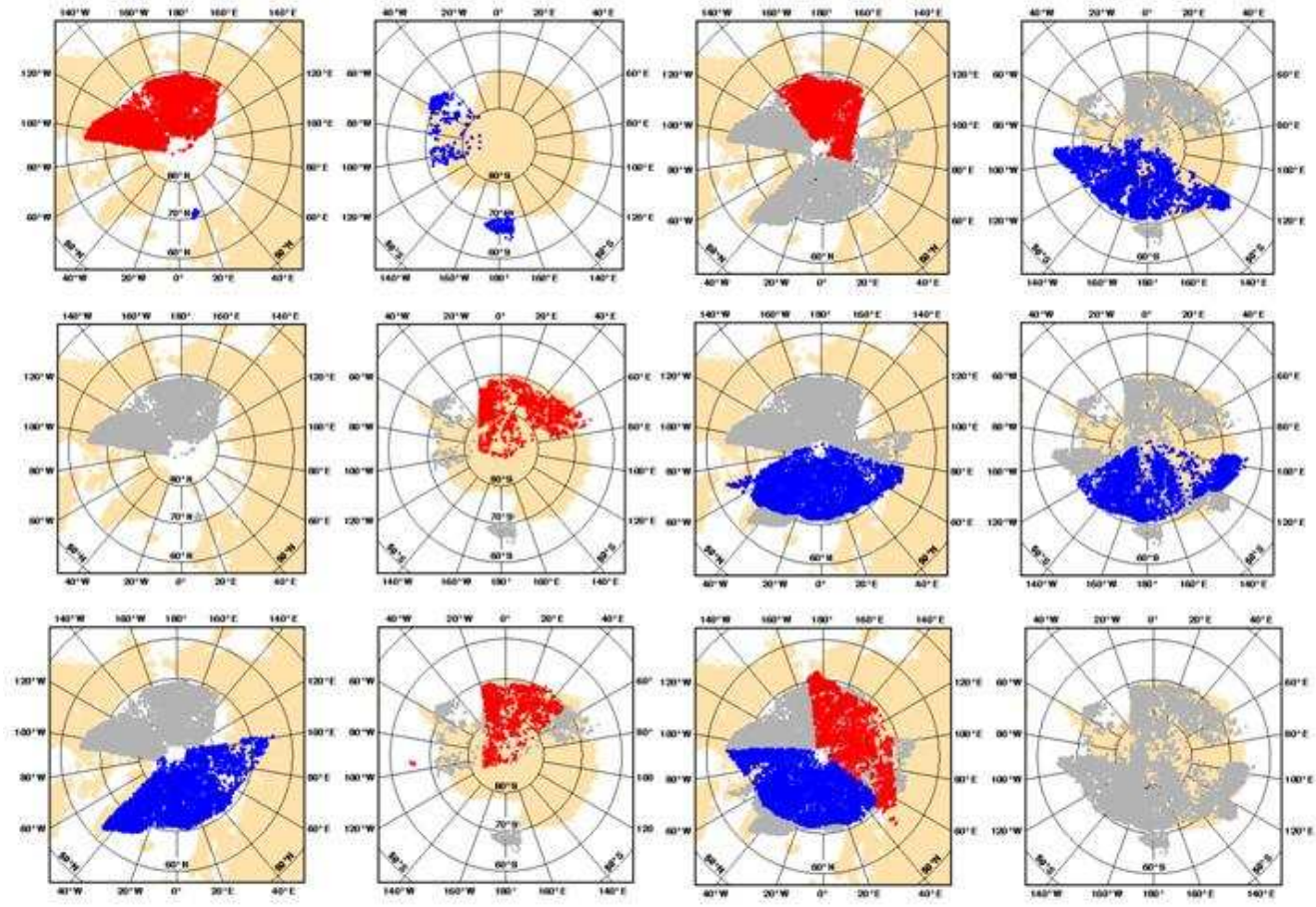


Figure 5: *Data coverage of the NESDIS MODIS polar winds for the 6z run on 16th January, 2005 over the North and South poles. The data is separated into 1 hour time-slots to show how the coverage builds up over the 6 hour window. Hour 1 is shown on the top left, working down and across to hour 6 on the bottom right. Winds valid in each hourly slot are shown in red (for Terra) and blue (for Aqua). Winds accumulated in previous hours are shown in grey.*

From Figure 3, we can see that data is produced with observation times at 25 minute intervals. This is because the satellites have an orbital period of ~100 minutes and therefore scan alternate poles every 50 minutes. Additionally Terra and Aqua cross the poles at different times. If we examine the first hour in Figure 5, there are 3 batches of data valid for this time. The first batch valid at 0302 is from Aqua in the SH, the second batch valid at 0326 is from Terra in the NH and the third batch valid at 0351 is from Aqua in the NH. It should be noted that some of the batches of data are missing due to the design of the processing schedule at NESDIS. The missing data is evident from the occasional longer than 25 minute gap between dots in Figure 3; for example at 300 minutes and 700 minutes. During the course of the 16th January there are 10 missing timeslots and 3 of these are during the 6 hour period covered by Figure 5 (including a NH slot in hour 2 and a SH slot in hour 6).

So what can we tell from Figures 3 and 5 about the future assimilation of these winds in the Met Office global model? Firstly, we can see from Figure 3 that very little data arrives in time for the main forecast run; in the case of the 16th January only 5% of the total 58 batches. Therefore the main impact from the MODIS winds will be via the background field generated by the update runs. On 16th January 55% of the batches arrived in time for the update runs, 28% arrived too late and 17% of the batches were never produced. Generally data in the first 3-4 hours of the time window arrives in time to be used in the update run. It is therefore encouraging that Figure 5 shows a fairly good coverage by the end of the fourth hour.

4. ASSIMILATION STRATEGY

The MODIS polar winds are a completely new dataset and differ in several ways from the geostationary winds used operationally. It was therefore necessary to examine the assimilation options in greater detail. Options include whether to use the winds from Aqua and Terra, which dataset to assimilate, which channels

to use and what quality control to apply. The choices made are discussed in greater detail in the following sections.

4.1. Use of winds from Terra and Aqua

The MODIS polar winds are produced using imagery from two polar-orbiting satellites: Terra and Aqua. The benefit of using data from both satellites can be seen in the data coverage plots in Figure 5. With data from both satellites, there is almost complete polar coverage in a 6-hour assimilation window.

With this in mind, the initial assimilation experiment at the Met Office used CIMSS data from both satellites; however, the experiment produced unexpected negative results. Assimilation experiments at ECMWF using CIMSS Aqua MODIS winds on top of their operational Terra winds also initially showed disappointing impact. In view of the poor results, we decided to test the robustness of our strategy to use winds from both Aqua and Terra, repeating our original MODIS experiment with data from Terra only and Aqua only (see Table 1 for more details).

MODEL DETAILS	Low resolution (100 km) Met Office Unified Model (Cullen et al., 1997)
DATA ASSIMILATION	3D-VAR (Lorenc et al., 2000)
PERIOD OF EXPERIMENT	11th May – 5th June 2003
BLACKLISTING	All clear-sky water vapour (CSWV) winds All winds below 400 hPa over land All IR winds below 700 hPa over sea All cloudy WV winds below 550 hPa over sea
THINNING BOX SIZE	140 km x 140 km x 100 hPa
EXPERIMENT DETAILS	CONTROL: No MODIS winds TRIAL A: Winds from Aqua and Terra TRIAL B: Winds from Terra only TRIAL C: Winds from Aqua only

Table 1: *Details of the CIMSS MODIS assimilation experiments at the Met Office*

The results of the single satellite experiments were very similar, with both showing negative impact in the southern hemisphere, but less so than the original experiment using data from both satellites together (see Figure 6). Percentage root mean square differences of greater than 2% are considered significant. Positive root mean square differences indicate a negative impact compared with the control trial without the MODIS winds.

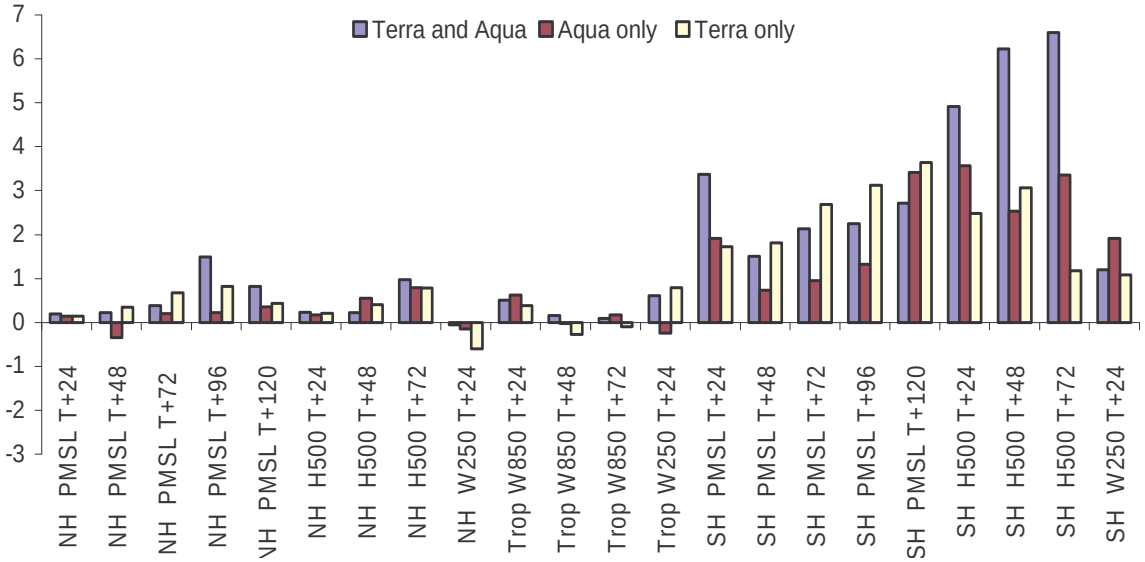


Figure 6: *Changes in % root mean square difference between the experiments and control over the course of the trials for certain forecast parameters (pressure at mean sea level (PMSL), 500 hPa geopotential heights (H500), 850 hPa and 250 hPa wind fields (W850 and W250)). Forecasts are verified against selected observations.*

In addition to the assimilation experiments, we also compared monitoring statistics for the two satellites against the Met Office model background. Table 2 shows the statistics for February 2004. The average

speed bias and root mean square vector differences of the Terra and Aqua winds are comparable. Compared to some AMVs the speed bias values in table 2 are small, but it is interesting that most months show a fairly consistent slow speed bias relative to the Met Office model background winds.

		Terra		Aqua	
		Speed Bias	RMSVD	Speed Bias	RMSVD
Clear Sky WV	NH	-0.7	5.9	-0.5	5.3
	SH	-0.9	6.3	-1.0	6.3
Cloudy WV	NH	-0.6	5.5	-0.6	5.5
	SH	-0.8	7.1	-1.0	6.9
IR	NH	-0.6	5.3	-0.5	5.3
	SH	-0.4	5.8	-0.5	5.7

Table 2: *Speed bias and root mean square vector difference statistics for Terra and Aqua for February 2004, calculated against the Met Office model background. Statistics are calculated separately for each channel and hemisphere.*

Other NWP centres presented similar results from comparative studies of the Terra and Aqua winds at the 7th International Winds Workshop in Helsinki in 2004 (e.g. von Bremen, 2004). It was generally agreed that the winds are of similar quality and all centres plan to use the winds from both satellites operationally.

4.2. Use of the NESDIS MODIS dataset

All the assimilation experiments using the CIMSS-processed MODIS winds showed a large negative impact in the southern hemisphere. Some other centres had also encountered problems including CMC and JMA (Sarrazin and Tokuno Pers. Comm.). In December 2003, a second product became available from NESDIS. Comparisons of the two products at NESDIS uncovered unexpected differences. Further investigation indicated that the main differences were in the vector direction (e.g. von Bremen et al., 2004). Figure 7 shows an example of the poorer fit of the vector direction of the CIMSS MODIS winds compared with the Met Office model background.

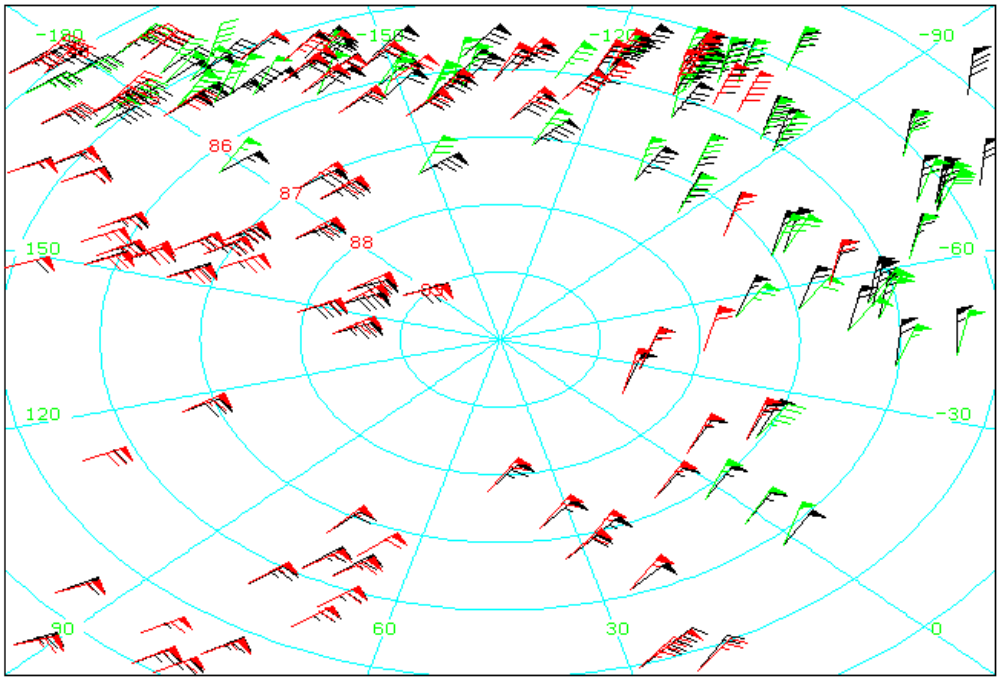


Figure 7: *Comparison of the NESDIS MODIS winds (in red) and the CIMSS MODIS winds (in green) with the Met Office model background (in black). All winds shown are valid for the same time on the 12th January and are located at 450 hPa. Note the better agreement of the NESDIS winds with the Met Office model background. The CIMSS winds are similar in speed to the background winds, but the directions agree less well.*

A significant improvement in the statistics against model backgrounds was observed for the NESDIS MODIS winds. Figure 8 shows a time series plot of root mean square vector differences between the CIMSS and NESDIS MODIS datasets and the Met Office model background for the first week of February, 2004. The statistics shown are for the infrared medium level northern hemisphere winds from Terra only. In general, the NESDIS MODIS winds show substantially smaller root mean square vector differences against the Met Office model background. Other channel, satellite, level and hemisphere combinations show similar results.

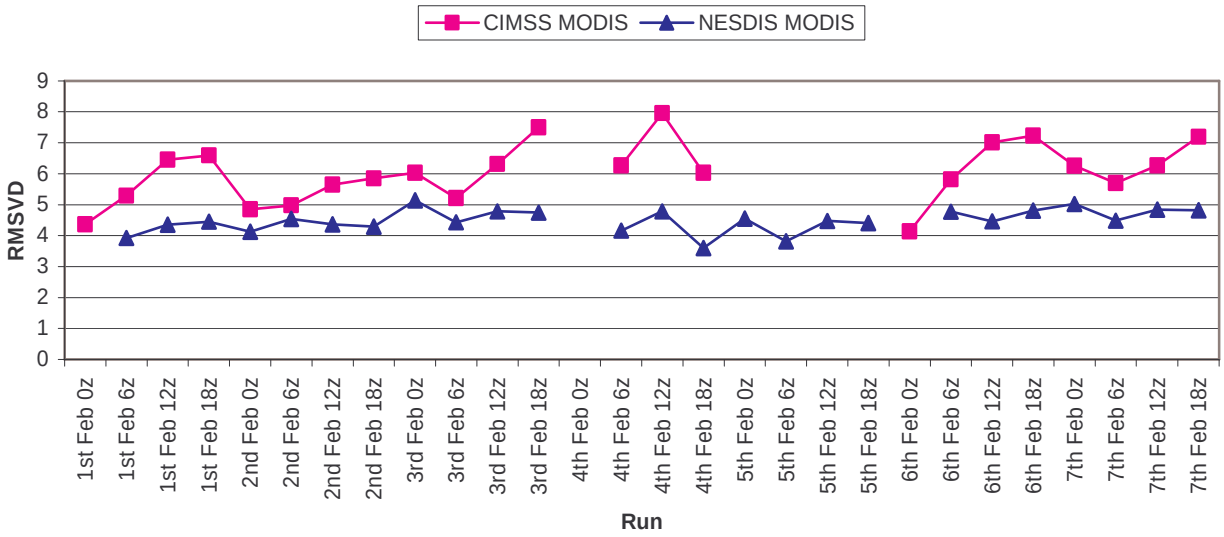


Figure 8: *Time series of the root mean square vector differences between the MODIS observations and the Met Office background for the first week of February 2004. The statistics shown are for the IR, medium level, NH Terra winds produced by each centre. Note the lower root mean square vector differences for the NESDIS MODIS winds throughout the period. The gaps are due to missing data.*

What is the cause of the differences between the CIMSS and NESDIS datasets? The production processes at CIMSS and NESDIS were very similar, but there were a few technical differences. One major difference between the centres was a more accurate first guess used in the tracking at NESDIS. At CIMSS the Navy/NOGAPS models was used without time interpolation and at NESDIS the NCEP/GFS model was used with time interpolation (Daniels, Pers. Comm.). A second difference was the image used for tracer selection. At CIMSS the first image was used and at NESDIS the middle image was used. It is not yet known which was the major factor, but if it is the first difference it suggests a dependence of the final wind on the first guess. This dependence is not ideal as the observations should be independent of model backgrounds. However, it is unlikely we will ever receive entirely model-independent data. Model information is used at various stages in the wind production.

At the 7th International Winds Workshop in June 2004 it was agreed that all new developments to the MODIS product would be tested first at CIMSS and then migrated to NESDIS as long as the majority of users are happy. To allow a more meaningful comparison, the CIMSS processing was updated in July 2004 to mimic the NESDIS processing, although there are still some small differences (e.g. Forsythe and Doutriaux-Boucher, 2005). In order to evaluate the changes at CIMSS, we plan to continue monitoring both the CIMSS and NESDIS MODIS polar winds, although only the NESDIS winds are used operationally. As part of our commitment, we are generating monthly statistics of both MODIS products against the Met Office model background. The results are available from the NWP SAF AMV monitoring site at http://www.metoffice.gov.uk/research/interproj/nwpsaf/satwind_report/index.html.

4.3. Use of IR, cloudy WV and clear sky WV winds

MODIS winds are generated using the 11µm infrared (IR) window channel and the 6.7µm water vapour (WV) absorption channel. WV winds are further distinguished as cloudy or clear sky. In the assimilation of the geostationary winds, all clear sky WV winds are rejected. This is mostly due to uncertainties in their height assignment and poor O-B statistics. Additionally, with 4D-Var it is possible to assimilate clear-sky radiances directly. For MODIS, however, the clear sky WV winds show comparable root mean square vector differences to the cloudy WV and IR winds (see Figure 9 and Table 2) and there is not yet a MODIS clear-sky radiance product available. Consequently the operational strategy is to use the IR, cloudy and clear sky WV winds. The more negative speed bias of the clear sky WV winds in Figure 9 is misleading. In general both the clear sky and cloudy WV winds have more negative speed biases than the IR winds, but there is a

strong seasonal dependency, with more marked negative bias in the summer hemisphere. The apparent more negative speed bias of the clear sky WV winds in Figure 9 is due to the greater number of clear sky WV winds in the NH during this month.

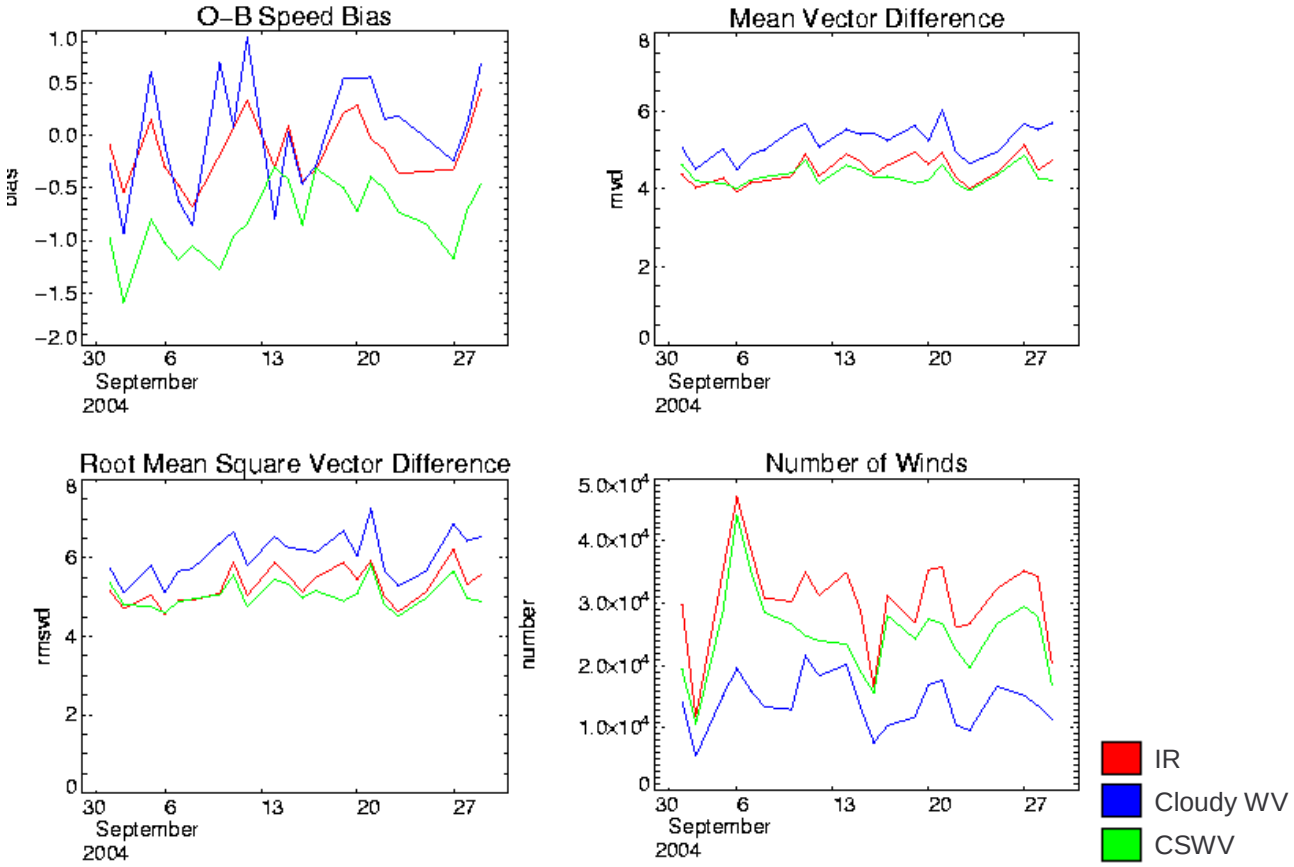


Figure 9: *Daily statistics for the NESDIS Terra winds compared to the Met Office model background for September 2004. Generally the clear sky water vapour (CSWV) winds have slightly lower root mean square vector differences and mean vector differences.*

4.4. Blacklisting and thinning

In the early CIMSS MODIS experiments, the blacklisting and thinning applied to the MODIS winds were very similar to those used operationally at ECMWF. Since then we have made a few modifications based on a combination of monitoring results and discussions with CIMSS about limitations of the height assignment methods. In our first NESDIS MODIS experiment we blacklisted all WV winds below 400 hPa, a policy we apply to the geostationary winds. However, it became apparent that by doing so we were removing the majority of the WV data. Figure 10 shows the distribution of winds from the different channels. It is clear from this figure that a threshold of 400 hPa would remove a large number of the cloudy and clear sky WV winds, an effect that is worse in the winter hemisphere (NH in Figure 10). The main reason for the lower heights of the WV winds in the polar regions is due to the low water vapour amounts. The WV 6.7 µm channel is able to see lower in the atmosphere. The channel can become contaminated by the surface in regions where the precipitable water is less than 0.3-0.4 cm (Key et al, 2004). In subsequent trials, a threshold of 600 hPa was applied instead.

Table 3 shows the quality control applied in the Met Office NESDIS MODIS assimilation experiments. Also shown, is the quality control applied operationally at ECMWF. In all cases the IR, cloudy WV and clear sky WV winds from Aqua and Terra are used.

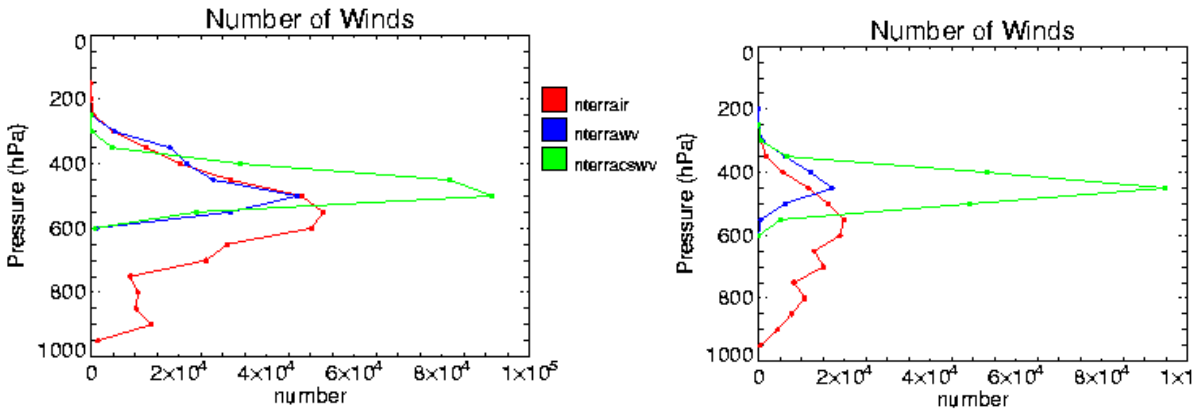


Figure 10: *Number of NESDIS MODIS Terra winds in each 50 hPa pressure bin for December, 2004 in the NH (left) and SH (right). Unlike the geostationary winds that are mostly at high (100-400 hPa) or low level (1000-700 hPa), the majority of MODIS winds are located at mid-levels (400-700 hPa). The winds are generally located slightly higher in the atmosphere in the summer (SH in this case).*

	Blacklisting	Thinning
ECMWF	• All winds below 400 hPa over land • All WV and CSWV winds below 550 hPa over sea • All IR winds below 700 hPa over sea	Was 140 km x 140 km on model levels. Now changed to 200 km x 200 km on model levels
Trial 1	• All winds below 400 hPa over land • WV and CSWV below 400 hPa everywhere • IR below 600 hPa over land and sea ice	250 km x 250 km x 100 hPa
Trial 2	• All winds below 400 hPa over Greenland and Antarctica • WV and CSWV below 600 hPa everywhere • IR below 600 hPa over land and sea ice	250 km x 250 km x 100 hPa
Trial 3	• All winds below 400 hPa over Greenland and Antarctica • WV and CSWV below 600 hPa everywhere • IR below 600 hPa over land and sea ice	200 km x 200 km x 100 hPa

Table 3: *Quality control used in the three NESDIS MODIS assimilation experiments. Also shown is the set-up used operationally by ECMWF in 2004.*

The thinning box size was increased to 250 km in our initial NESDIS MODIS experiment following the poor results using 140 km with the CIMSS MODIS winds. AMV data has been shown to have statistically significant spatial error correlations for distances of up to 800 km (Bormann et al., 2002). Whilst it is not recommended that we thin the data to 800 km, it is recognised that if we do not thin the data enough, the observations (with their correlated errors) will tend to pull the analysis consistently in one direction and thus the analysis and short-term forecast will overfit to this data type. The choice of thinning box size is therefore a balance between using more of the wind information and avoiding problems due to spatial error correlations. Trial 3 uses a box size of 200 km. This is most similar to the 2 degree box size we use for the geostationary AMV data.

Several blacklisting changes were made. Some of the differences between our settings and ECMWFs are due to our ability to distinguish sea ice from sea and to isolate the main areas of high land (Greenland and Antarctica). The MODIS wind height assignment is more problematic over cold surfaces (land and sea ice) and therefore the blacklisting thresholds could be relaxed over sea. The height assignment is thought to be most problematic over high land and so the thresholds are most restrictive in these areas. The lower limit for the WV winds usage was set at 600 hPa based on an analysis of the statistics against the Met Office model background (see Figure 11).

One final point to note about the first season trials of the NESDIS MODIS winds during January-February 2004 is that we did not have access to real-time data at this point. To try and mimic the real situation as well as possible we allowed all MODIS data into the main update run and no data into the main forecast run. As a result we would have been assimilating data in the 5th and 6th hours of the time window, which normally does not arrive in time. Conversely we would miss out on the occasional MODIS batch that arrives in time for the main forecast run.

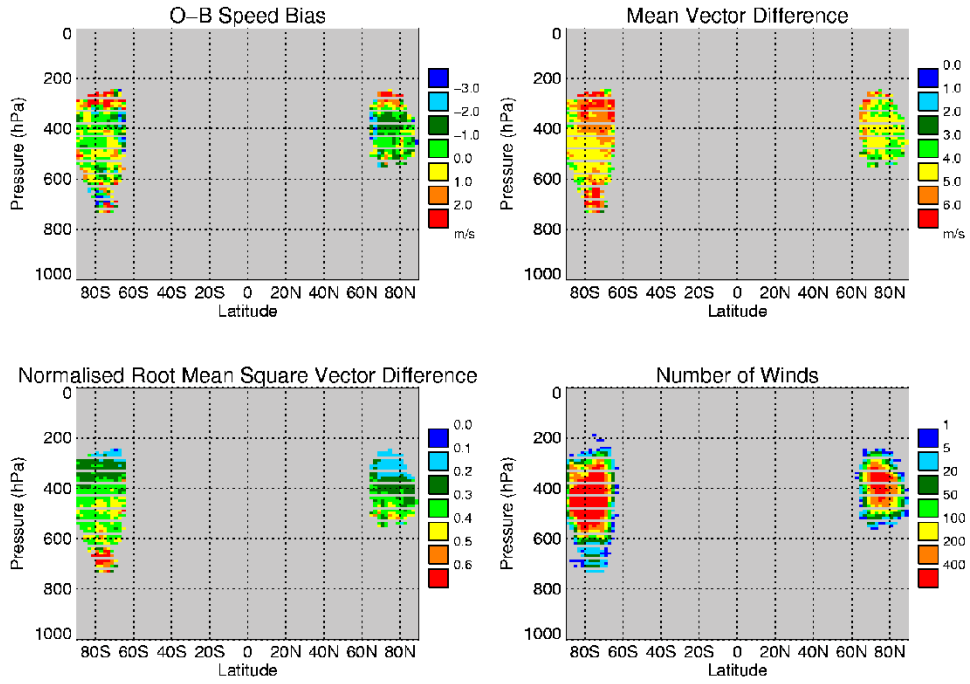


Figure 11: *Plots of statistics as a function of pressure and latitude for the NESDIS MODIS Terra cloudy WV winds compared to the Met Office model background for the month of October, 2004. Note the higher normalised root mean square vector difference and mean vector difference for winds below 600 hPa in height.*

The NWP index results for the three trials are shown in Figure 12. All three experiments show improvement in the majority of the key forecast parameters. Overall, Trial 2 produces the best NWP index against observations, but this is partly due to the strong weight given to the Tropical W250 T+24 forecast. Trial 2 also exhibits more variable performance in the time-series. As a result, the decision was taken to use the configuration applied in Trial 3. The blacklisting is closest to recommended usage and is less restrictive than for Trial 1. The thinning is also closest to the resolution we use for the geostationary winds.

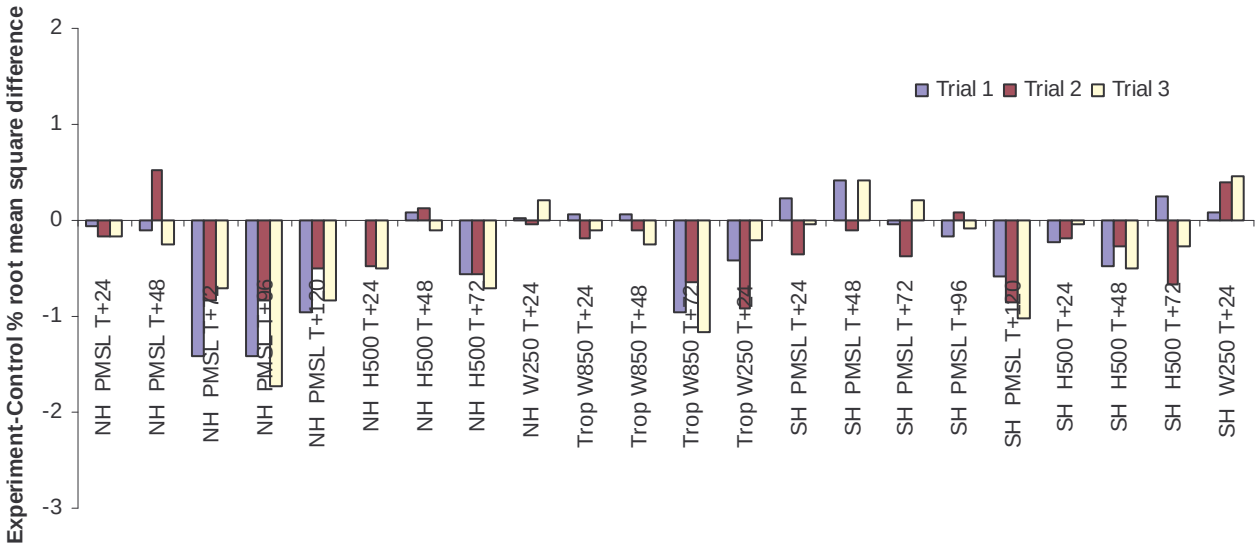


Figure 12: *Changes in % root mean square differences between the NESDIS MODIS experiment and control over the course of the trials for certain forecast parameters (pressure at mean sea level (PMSL), 500 hPa geopotential heights (H500), 850 hPa and 250 hPa winds fields (W850 and W250)). Forecasts are verified against observations. Negative % root mean square differences indicate a positive impact compared to the control trial without MODIS winds. Overall the impact is slightly positive, with most impact seen at medium range.*

The results of all the NESDIS MODIS experiments are much better than those seen with the CIMSS winds. The improvement is thought to be mainly due to the use of the NESDIS MODIS winds instead of the CIMSS

MODIS winds, but the use of a different season may also affect the results. This may be particularly critical for polar data where winter and summer may produce large contrasts in verification. In order to ensure the usefulness of the MODIS data during a southern hemisphere winter, a second season trial was run using the same set-up as Trial 3. Both seasons are discussed in greater detail in sections 5 and 6.

5. EXPERIMENT DETAILS

Two trial seasons were selected in January-February and July-August 2004. The experiment details are shown below:

1st season: 24th Jan – 17th Feb 2004

Control: N144, 38 vertical levels global model, 3DVAR assimilation. Data assimilation as in the 2004 Met Office Satellite Spring Upgrade, but without the EARS (EUMETSAT Advanced Retransmission Service) ATOVS winds.

Trial: As for the control except NESDIS MODIS IR, cloudy WV and clear sky WV winds assimilated. The blacklisting and thinning options are shown in Figure 13. Due to lack of access to real-time MODIS data, all MODIS winds were allowed into the update run, but none into the main forecast run.

2nd season: 21st Jul – 21st Aug 2004

Control: N216, 38 vertical levels global model, 3DVAR assimilation. Data assimilation as operational at the Met Office in July 2004.

Trial: As for the control except NESDIS MODIS IR, cloudy WV and clear sky WV winds assimilated. The blacklisting and thinning options are shown in Figure 13.

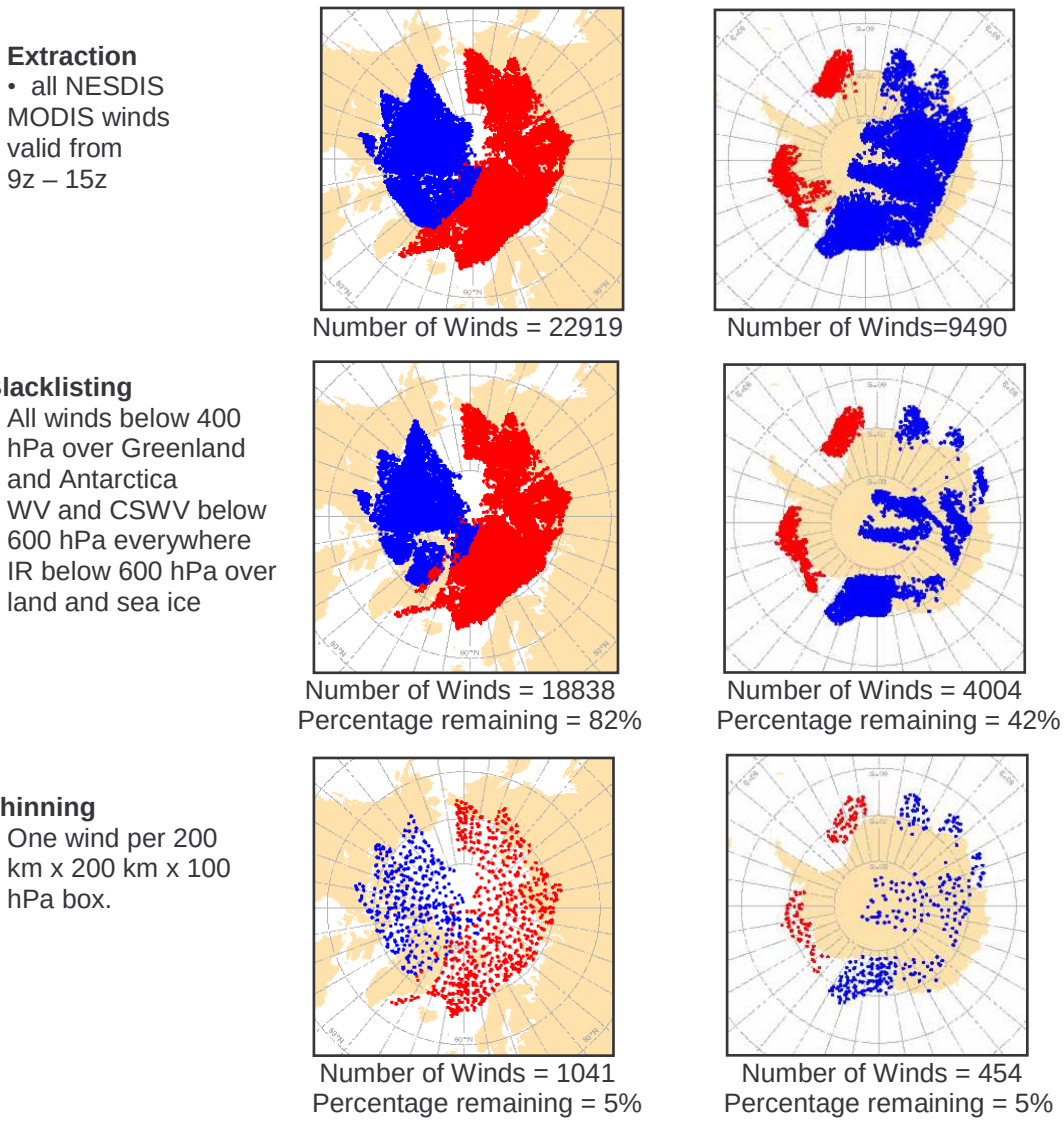


Figure 13: *Data coverage plots showing the effect of the various quality control steps (example from 24th January 2004, 12z run). Terra MODIS winds are shown in red and Aqua in blue.*

From Figure 13 it is apparent that the quality control removes most of the MODIS data. Only about 5% of the MODIS winds are assimilated. Despite the loss of data, the spatial coverage is still good.

6. RESULTS

6.1. Analysis impact

The mean analysis differences between the control and MODIS trials are concentrated in the polar regions. The differences are generally small, between ±2 m/s for the winds and ±20 m for the 500 hPa geopotential height. These differences are averages over the course of the trial; the day to day differences will be bigger.

There are a couple of tests to assess the quality of the analyses. Firstly, we can look at the fit of other observations to the analysis and first guess. Secondly we can look at the rms analysis increments over the course of the trial. Normally, when analyses are improved, the fit to other observations will improve and the rms analysis increments will go down. The latter can be understood as the rms analysis increment can be considered as the amount the first guess has to be corrected. Smaller analysis increments indicate a good consistency of the assimilation. This result does not always follow, however, when data is added to a data sparse region as is the case for the MODIS polar winds. In these situations it is not uncommon for the rms analysis increments to increase as the addition of data may lead to less smooth analyses and short-term forecasts, which may verify less well. With this in mind, the results of the two tests for the MODIS winds are quite encouraging. The global fit of other observations to the first guess and analysis are not significantly altered. The rms analysis increments are generally reduced in the NH, particularly at 500-250 hPa. The rms increment differences in the SH are more mixed (e.g. Figure 14).

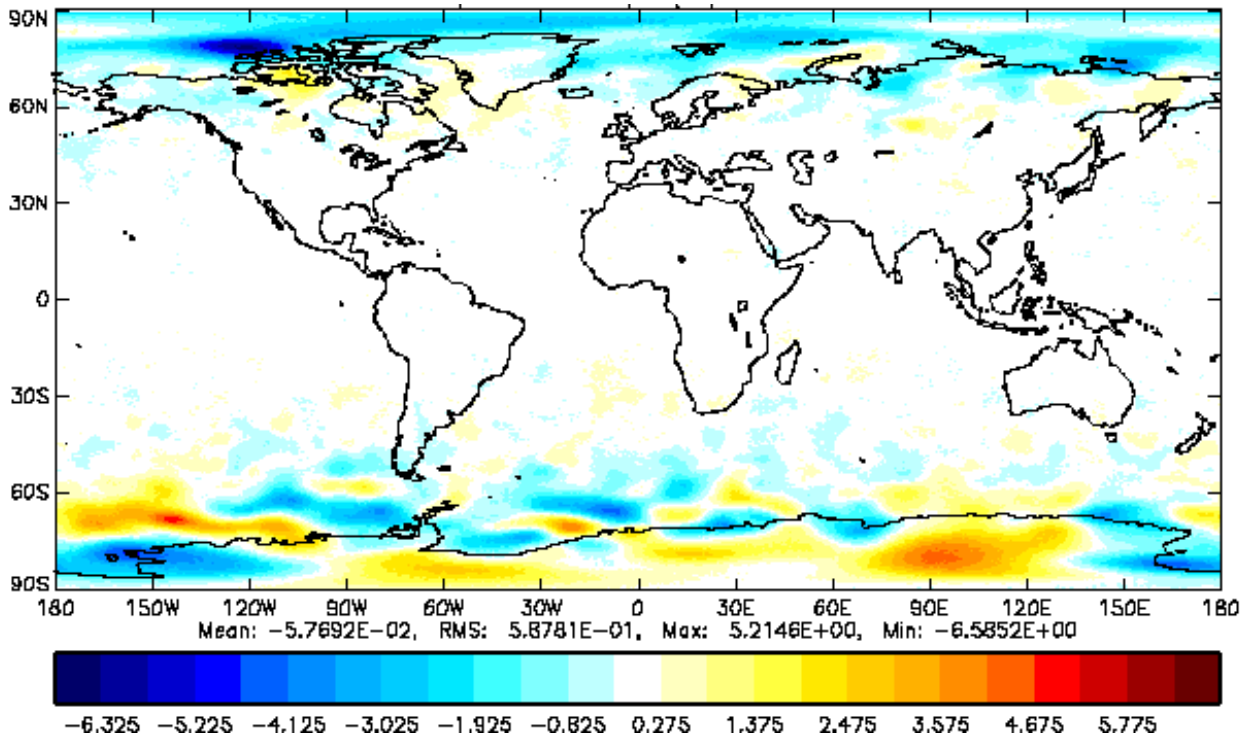


Figure 14: *Difference in the 500 hPa geopotential height rms analysis increments between the MODIS and control trials (21st Jul – 21st Aug, 2004). Areas in blue (negative values) indicate regions where the MODIS trial has smaller rms analysis increments.*

6.2 Forecast parameters contributing to the Met Office's global NWP index

The primary tool used at the Met Office for assessing whether an impact trial has improved the forecast compared with the control run is the NWP index. The global NWP index is produced from a weighted sum of forecast field statistics for certain parameters at selected forecast times (see Annex 1). Table 4 summarizes the NWP index results from the two trial seasons.

	Verification versus observations	Verification versus analyses
25th Jan – 17th Feb 2004	0.325	0.147
21st Jul – 21st Aug 2004	0.306	1.340

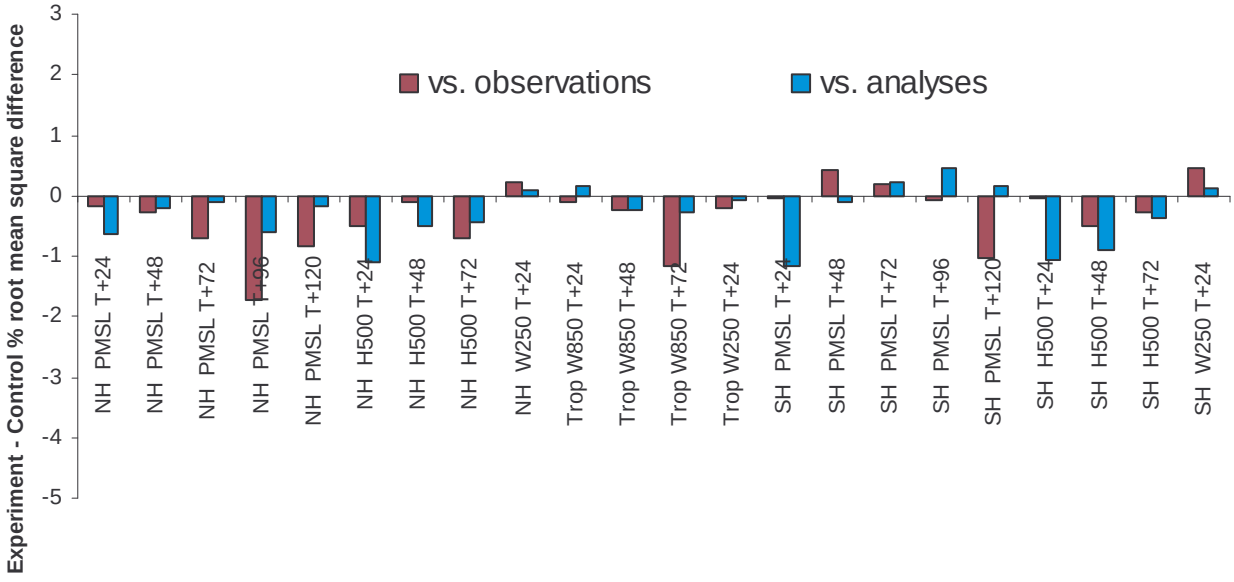
Table 4: *NWP index results for the NESDIS MODIS experiments. Positive indices indicate an improvement over the control.*

Figure 15 are bar charts of the percentage change in root mean square difference for the trial versus control for the NWP forecast parameters verified against observations and analyses. A negative bar indicates that the difference has decreased and is a positive result for the trial. A percentage rms forecast difference of 2% or more is considered significant. In the first season trial, all the bars are less than 2% in magnitude, and most are negative indicating that the assimilation of the NESDIS MODIS winds has had a small positive impact overall. In the second season trial, several fields show significant improvement in the northern and southern hemispheres. The verification against analyses is particularly impressive, with the biggest improvement in the northern hemisphere 500 hPa height field. The improvement is also reflected in the final NWP index against analyses, with a value of 1.3.

The second season trial results show much larger impacts for many of the forecast parameters, particularly in the verification against analyses. A small improvement might be expected due to the higher resolution of the 2nd season model (running N216 rather than N144). We might also expect some differences due to the time of year. There is, however, one other important difference. In the first season trial, the MODIS winds were not available in real-time and our set-up led to more data being used in the update run and less in the main forecast run than we would have used operationally. The second season trial was planned to test the operational real-time usage, however, it was belatedly identified that the wrong cut-offs had unintentionally been used in the obstore generation. A time cut-off of 175 minutes rather than 100 minutes was used for the main forecast run and a cut-off of 420-435 minutes rather than 405 minutes was used for the update run. As a result more MODIS data would have been used in both the main forecast and update runs than would be the case operationally. It is believed that this may have led to larger impacts; however, the overall benefit of the MODIS winds is likely to be valid. Although the longer cut-offs are not ideal for estimating the true impact of the MODIS winds, the second season trial may provide a guide to the expected impact of more timely MODIS data. There are several changes, discussed in greater detail in section 7, which could lead to improvements in the timeliness of the MODIS winds.

Extended tables that detail the impact on 369 forecast parameters, show a similar picture, with more impact in the 2nd season trial and improvements concentrated in the northern and southern hemispheres with little change in the tropics. Overall, the strongest improvements are to the temperature, height and wind fields at mid levels (850 hPa – 250 hPa), but improvements are also seen at low levels (in the pressure at mean sea level) and some of the upper level fields, particularly at longer forecast range.

a) First season: 25th January – 17th February



b) Second season: 21st July – 21st August

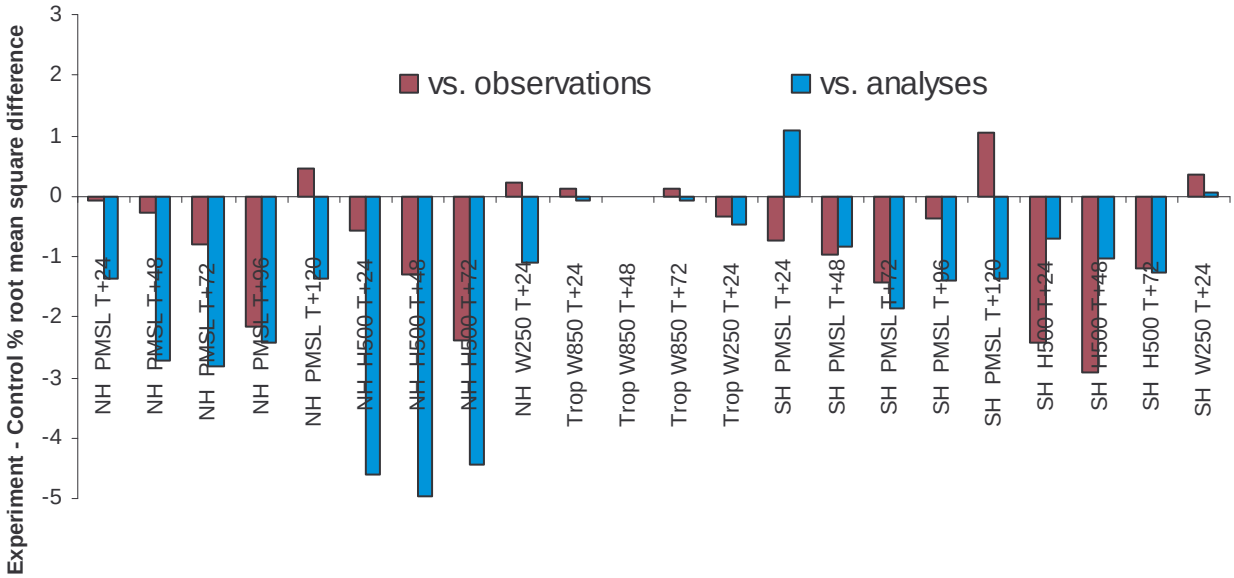


Figure 15: *Changes in % root mean square difference between the experiment and control over the course of the trials for certain forecast parameters (pressure at mean sea level (PMSL), 500 hPa geopotential height (H500), 850 hPa and 250 hPa wind fields (W850 and W250)). Forecasts are verified against selected observations and analyses. Negative root mean square differences indicate a positive impact compared with the control trial. % root mean square differences with magnitudes of > 2% are considered significant.*

6.3. Comparison to radiosondes

Figure 16 shows the average fit of the Control and MODIS experiment northern hemisphere T+72 forecasts to radiosonde data. The plots show the mean difference and rms difference between the temperature and wind speed forecasts and sonde values. The MODIS data appears to slow down the mid level T+72 wind speeds, giving a more negative speed bias relative to radiosondes. Despite this, both rms difference plots show an improvement in the fit of the forecasts to sonde data from the surface to 200 hPa due to the use of MODIS polar wind data.

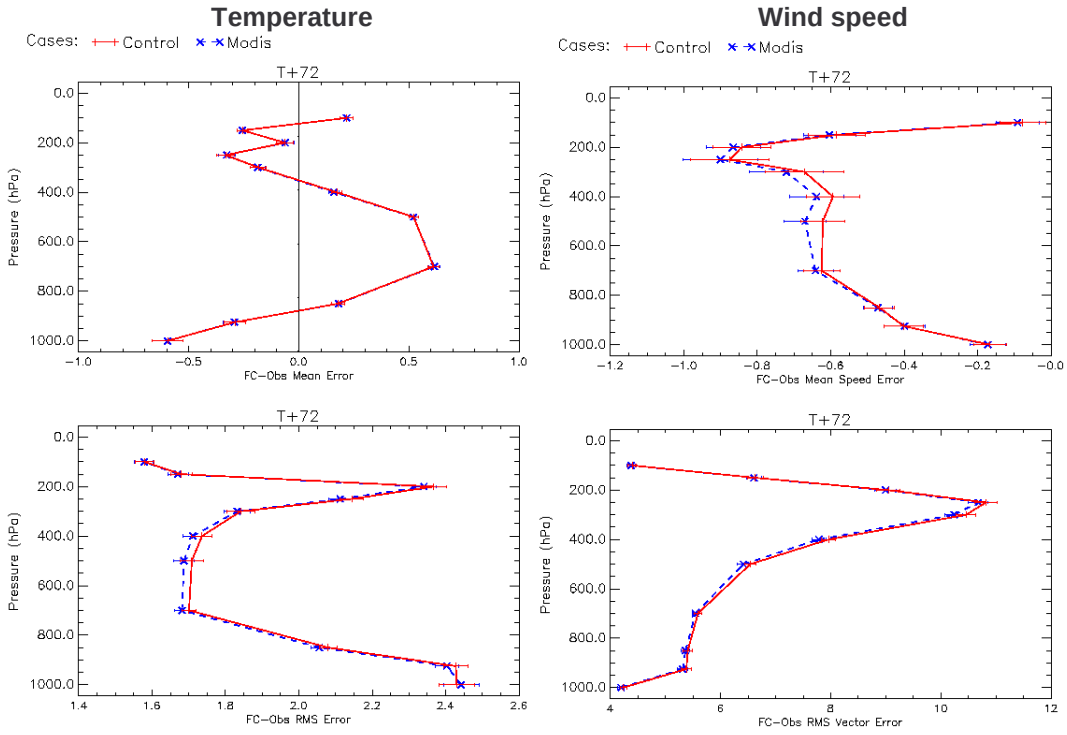


Figure 16: *Mean and rms difference between NH 72 hour forecast temperature and wind speed compared with radiosonde temperature and wind speed as a function of pressure.*

6.4 Forecast-Analysis Difference Plots

Another way to evaluate the impact of the MODIS winds is to look at forecast-analysis differences plots. If we consider the analysis as being close to truth, the forecast-analysis differences give us an idea of the forecast error. By looking at a series of forecast periods from the same day, we can track the forecast error evolution. Figure 17 shows the forecast error for forecasts made on 14th August. The forecast error increases with forecast range, as expected, in both the control and MODIS experiments. However, the size of the error is consistently smaller in the trial assimilating MODIS winds. Figure 17 also illustrates how the MODIS winds, which are only available polewards of 65° latitude, can influence and improve medium-range forecasts at mid-latitudes.

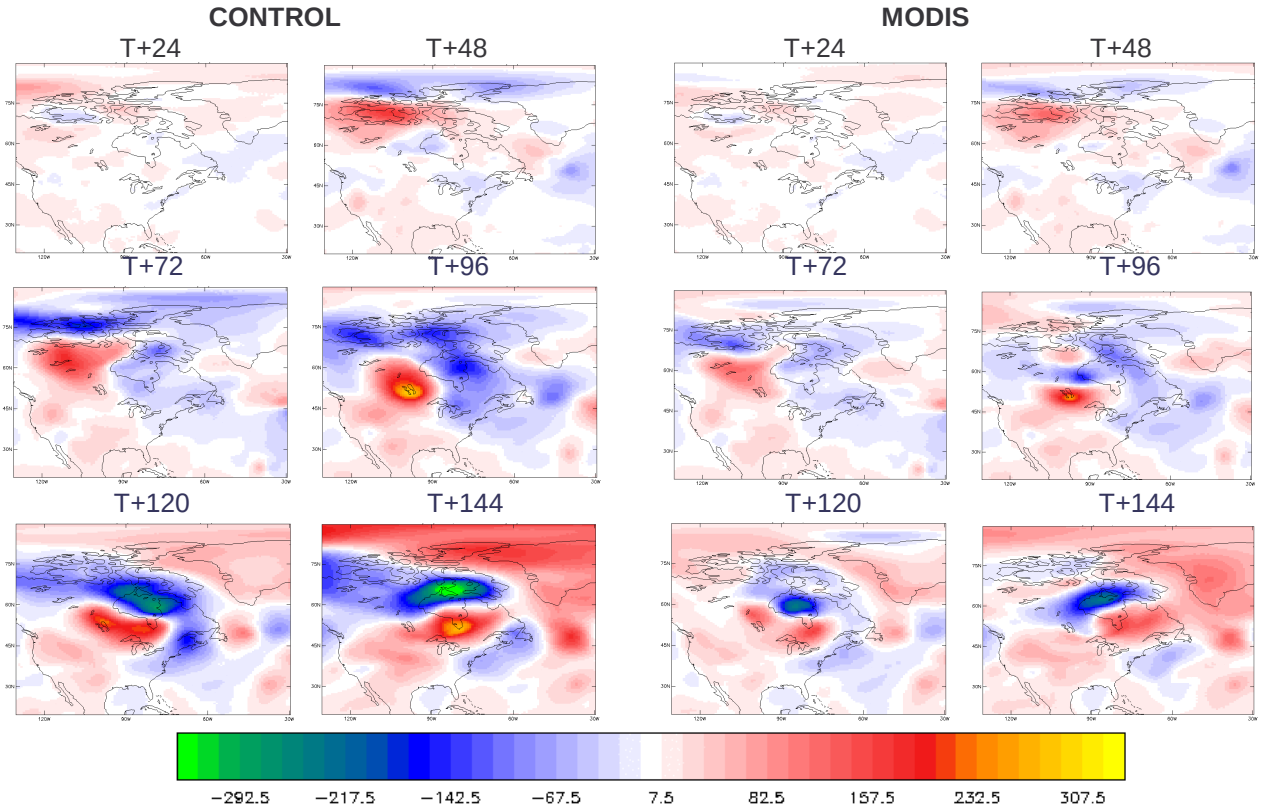


Figure 17: *Forecast error evolution for 500 hPa geopotential height forecasts generated on 14th August 2004 for the control and MODIS trials. Forecast error is calculated as the forecast field minus the trial analysis valid at that time. Note the smaller errors for all forecast ranges in the MODIS experiment compared to the control. The figure also illustrates how information added to the polar regions spreads equatorwards improving the medium range forecasts at lower latitudes.*

7. FUTURE IMPROVEMENTS

Development work is ongoing at CIMSS and NESDIS to improve the MODIS winds. Some of the improvements include: developing a parallax correction, use of alternate Aqua and Terra passes, production of winds from additional MODIS channels, modification to the size of the search area, improvement to the height assignment and use of direct broadcast stations. The developments should help to reduce dependence on first guess, improve the quality of the winds and reduce the time lag between observation valid time and receipt time (e.g. Santek et al., 2004; Key et al., 2004). Some of the proposed changes are discussed in more detail below.

7.1. Use of direct broadcast

Reduction in lag time is possible through the use of direct broadcast. The time lag could be reduced for some passes by 100 minutes or more (e.g. Key et al., 2006). Looking at Figure 3, it is easy to see how a reduction in delay of this size, could allow us to use more data in the main forecast runs and to use almost all the winds in the update runs.

The establishment of direct broadcast stations is progressing with winds being routinely produced at McMurdo station in Antarctica and Tromso. There are plans to include another Antarctic station and 2 more Arctic stations in the near future. The direct broadcast data should soon be available in BUFR format for NWP users.

7.2. Use of alternate Aqua and Terra images

Currently the MODIS winds are generated from image triplets from the same satellite. It is, however, possible to use alternate Aqua and Terra overpasses to generate the winds. This would lead to an improved timeliness of 25-75 minutes and could also improve the equatorward coverage. This would help reduce the data gap between the geostationary and polar winds (see Figure 18).

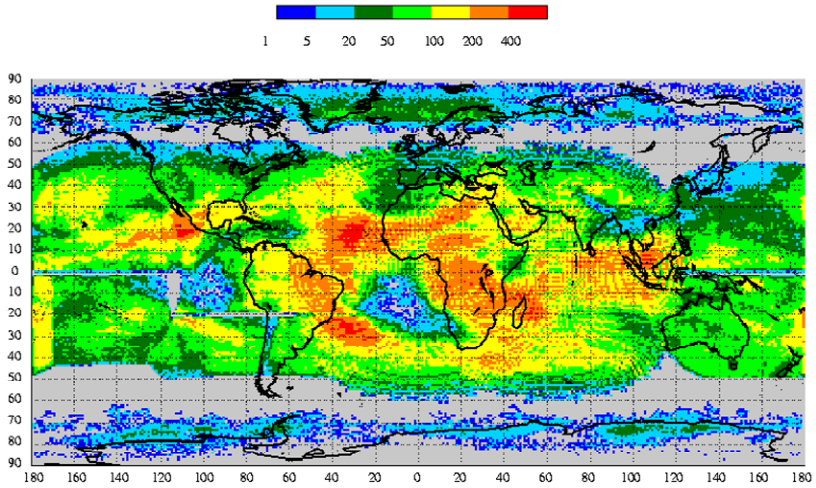


Figure 18: *Plot showing the number of winds in each 1 degree by 1 degree box for all high level WV winds for December 2004. Note the data gap between the geostationary and polar data between ~60-65° latitude.*

7.3. Additional channels

MODIS winds may also be produced from the 1.6μm and 3.7μm channels. The 3.7μm channel is better at snow-cloud discrimination.

7.4. Changes within the Met Office

Much of the continued effort with MODIS winds at the Met Office will be adapting to changes implemented at CIMSS and NESDIS. CIMSS plan to carry out all the improvements on their dataset and when most of the users are happy these changes will be migrated to NESDIS. We plan to continue monitoring the CIMSS dataset in order to evaluate changes and provide feedback. Some of the changes, for example the production of winds from extra channels, may require further trialling.

Alongside this MODIS specific work, there are also some more general considerations of how to improve the assimilation of AMVs; for example, re-evaluating observation errors and use of more forecast-independent data. Currently we have only examined the final winds produced by NESDIS, both for the MODIS winds discussed here and for the GOES winds we use operationally. All these winds pass through an autoeditor, which can modify the speed and height of the winds to improve the fit to a model background and surrounding winds. We would like to examine the original winds before this step in the processing. In addition, quality indicators are available with the MODIS data and this information has not yet been examined or used.

7.5. Beyond MODIS

Aqua and Terra are NASA-owned research satellites, which have been in orbit since 2002 and 1999 respectively. In 2005 they were granted 5 years further funding. EUMETSAT and NESDIS are planning to produce winds using AVHRR imagery, which will enhance the polar AMV coverage and provide continuity beyond Terra and Aqua. The main disadvantage is the lack of WV absorption band, with none planned on future polar imager instruments until at least 2016. The winds produced using the IR channel look of equivalent quality to those from the WV channel (e.g. Figure 9), but there would be some loss in coverage and recent assimilation experiments at ECMWF and GMAO suggest there would also be some loss in benefit for global NWP models, potentially halving the benefit (e.g. Thėpaut et al., 2006; Riishojgaard et al.,

2006b). One option being considered that could provide both IR and WV winds over the Northern Hemisphere earlier than 2016 is the use of a satellite in Molniya orbit, where the satellite spends most of its time at geostationary heights over the North Pole (Riishojgaard, 2004; Riishojgaard et al., 2006a). Two advantages of this orbit for the production of polar AMVs include improved timeliness compared with the MODIS winds and improved equatorward coverage (closing the gap with the geostationary winds). The main disadvantage is the provision only over the Northern Hemisphere. Other potential uses for the more frequent polar imagery provided from a Molniya orbit have been identified, but the proposal has not yet secured funding.

8. CONCLUSIONS

From the monitoring, assimilation experiments and investigations carried out at the Met Office we can draw the following conclusions:

1. The winds from Aqua and Terra are of comparable quality
2. The NESDIS MODIS wind product agrees better with the Met Office model background and gives better impact in assimilation experiments than the original CIMSS MODIS product.
3. Very little MODIS data arrives in time for the main forecast runs. Despite this limitation the latest experiments at the Met Office have produced positive impact in the northern and southern hemispheres. Overall, the strongest improvements are to the temperature, height and wind fields at mid levels (850 hPa – 250 hPa) at longer forecast range (T+72 onwards). As a result of these findings, the MODIS winds became operational in the Met Office global model in February, 2005.
4. Work will continue at the Met Office and at CIMSS to try and improve both the product and the way we use it. There is scope for improving the quality and timeliness of the MODIS winds, which should allow us to use more data and gain more benefit operationally.

9. ACKNOWLEDGEMENTS

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10. REFERENCES

Bormann, N. and J-N. Thėpaut, 2003. Impact of MODIS Polar Winds in ECMWF's 4DVAR Data Assimilation System. *Monthly Weather Review*, **132**, 929-940.

Cullen, M. J. P., T. Davies, M.H. Mawson, J.A. James, S.C. Coutler, A. Malcolm, 1997. An overview of numerical methods for the next generation UK NWP and climate model. *Numerical Methods in Atmospheric and Ocean Modelling*, Lin, C. A., R. Laprise, and H. Ritchie, Eds., volume **The Andre J. Robert Memorial Volume**, 425-444.

Forsythe, M. and M. Doutriaux-Boucher, 2005. Second analysis of the data displayed on the NWP SAF AMV monitoring website. NWP SAF Technical Report 20. Available at http://www.metoffice.gov.uk/research/interproj/nwpsaf/satwind_report/nwpsaf_mo_tr_020.pdf.

Key, J.R., D. Santek, C.S. Velden, N. Bormann, J-N. Thėpaut, L.P. Riishojgaard, Y. Zhu and W.P. Menzel, 2003. Cloud-drift and water vapour winds in the polar regions from MODIS. *IEEE Transactions on Geoscience and Remote Sensing*, **41**, 482-492

Key, J.R., D. Santek, C.S. Velden, 2004. Atmospheric motion vector height assignment in the polar regions: issues and recommendations. *Proceedings of the 7th International Winds Workshop, Helsinki. Available via EUMETSAT.*

Key, J., W. Straka III, D. Santek, C. Velden and R. Dworak, 2006. Satellite-derived winds at direct broadcast sites in the polar regions and AVHRR polar wind historical reprocessing efforts. *Proceedings of the 8th International Winds Workshop, Beijing. Available via EUMETSAT.*

Lorenc, A.C., S.P. Ballard, R.S. Bell, N.B. Ingleby, P.L.F. Andrews, D.M. Barker, J.R. Bray, A.M. Clayton, T. Dalby, D. Li, T.J. Payne and F.W. Saunders, 2000. The Met.Office Global 3-Dimensional Variational Data Assimilation Scheme. *Quart. J. Roy. Met. Soc.*, **126**, 2991-3012.

Riishojgaard, L.P., 2004. The case for launching a meteorological imager in a Molniya orbit. *Proceedings of the 7th International Winds Workshop, Helsinki. Available via EUMETSAT.*

Riishojgaard, L.P., B. Atlas, D. Chesters, K. Holmlund, J. Key, S. Kidder, A. Krueger, P. Menzel, J-N. Thėpaut, C. Velden and T. Vonder Haar, 2006a. The Molniya orbit imager. *Proceedings of the 8th International Winds Workshop, Beijing. Available via EUMETSAT.*

Riishojgaard, L.P., M. Sienkiewicz and G.P. Lou, 2006b. The impact on forecast skill of water vapor and window channel winds from MODIS. *Proceedings of the 8th International Winds Workshop, Beijing. Available via EUMETSAT.*

Santek, D.A., C.S. Velden and J.R. Key, 2004. Polar winds from MODIS: Project Status. *Proceedings of the 7th International Winds Workshop, Helsinki. Available via EUMETSAT.*

Thėpaut, J-N., N. Bormann and C. Delsol, 2006. Impact of atmospheric motion vectors on global numerical weather prediction. *Proceedings of the 8th International Winds Workshop, Beijing. Available via EUMETSAT.*

Velden, C.S., 2000. Exploratory satellite-derived winds research at CIMSS. *Proceedings of the 5th International Winds Workshop, Australia. Available via EUMETSAT.*

Von Bremen, L., J-N. Thėpaut and G. Kelly, 2004. Assimilation of polar winds and recent satellite winds impact studies at ECMWF. *Proceedings of the 7th International Winds Workshop, Helsinki, 2004. Available via EUMETSAT.*

ANNEX 1: THE MET OFFICE GLOBAL NWP INDEX

In order to provide an objective global assessment of data assimilation or model changes the Met Office uses a basket of forecast verification scores. Each score is weighted against its perceived importance to create a global index. Whilst this index is not sufficient to judge any change it can be a useful objective way to compare a number of changes without subjectively selecting a particular verification score which favours one change above another. The index has risen by 25% over 10 years so the importance of new changes can be judged against past performance.

The Index is compiled from mean sea-level pressure (PMSL), 500 hPa height (H500), 850 hPa wind (W850) and 250 hPa wind (W250). It is verified over the following areas: Northern Hemisphere 20N-90N (NH), Tropics 20N-20S (TR) and Southern Hemisphere 20S-90S (SH) and at forecast ranges from T+24 to T+120.

Once the forecast and persistence root mean square errors have been determined for a particular combination of parameter/area/forecast range the skill score is calculated. This is defined in terms of reduction of variance, i.e.

$S = 1 - r_f^2/r_p^2$

Where r_f is the rms forecast error and r_p is the rms persistence error.

The weight given to each verification field is shown in Table A.1.

		Forecast period				
		T+24	**T+48**	**T+72**	**T+96**	**T+120**
NH	**PMSL**	10	8	6	4	4
	H500	6	4	2		
	W250	12				
TR	**W850**	5	3	2		
	W250	6				
SH	**PMSL**	5	4	3	2	2
	H500	3	2	1		
	W250	6				

Table A.1: *Weights given to each forecast parameter in the Met Office global NWP index.*